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Comparison of cyclic fatigue behavior between C/SiC and SiC/SiC ceramic-matrix composites at elevated temperatures using hysteresis dissipated energy

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ABSTRACT

The fatigue behavior of cross-ply C/SiC and 2D woven SiC/SiC composites at elevated temperatures in air or steam condition have been investigated using the hysteresis dissipated energy. The evolution of fatigue hysteresis dissipated energy and hysteresis dissipated energy-based damage parameter of C/SiC and SiC/SiC composites have been analyzed. For SiC/SiC composite at 1000 °C in steam, the experimental fatigue hysteresis dissipated energy lies in the right part of the fatigue hysteresis dissipated energy versus interface shear stress curve, which indicates that the interface partially debonds during cyclic fatigue loading; however, for C/SiC composite at 800 °C in air, the experimental fatigue hysteresis dissipated energy lies in the right and left part of the fatigue hysteresis dissipated energy versus interface shear stress curve, which indicates that the interface completely debonds upon initial cyclic fatigue loading. By comparing the experimental fatigue hysteresis dissipated energy with theoretical computational values, the interface shear stress of C/SiC and SiC/SiC composites have been estimated. The interface shear stress of C/SiC composite at 800 °C in air decreases much more rapidly than that of SiC/SiC composite at higher temperatures in air or steam condition.

1. Introduction

With the demand for high thrust-weight ratio and more efficient aero engine, the temperature of the turbine sections will be raised to a level exceeding the limit of current metallic materials. New materials will have to be tested and validated at very high temperatures that surpass 1300 °C. Ceramic-matrix composites (CMCs) are lighter than superalloys and maintaining the structural integrity even at higher temperatures, desirable qualities for improving aero engine efficiency, and have already been implemented on some aero engines' components [1,2]. CMC durability has been validated through ground testing or commercial flight testing in demonstrator or customer gas turbine engines accumulating almost 30,000 h of operation. The CMC combustion chamber and high-pressure turbine components were designed and tested in the ground testing of GEnx aero engine [3]. The CMC rotating low-pressure turbine blades in a F414 turbofan demonstrator engine were successfully tested for 500 grueling cycles to validate the unprecedented temperature and durability capabilities by GE Aviation. The CMC tail nozzles were designed and fabricated by Snecma (SAFRAN) and completed the first commercial flight on CFM56-5B aero engine on 2015. CMCs will play a key role in the performance of CFM's LEAP turbofan engine, which would enter into service in 2016 for Airbus A320 and 2017 for Boeing 737 max.

CMCs are subject to fatigue upon cyclic mechanical and thermal loading. Understanding the damage mechanisms and damage evolution under fatigue loading represents an important step in the use of these materials [4]. The hysteresis loops appear as the fiber slips relative to matrix in the interface debonded region [5]. The shape, location and area of the hysteresis loops can be used to reveal the internal damage evolution of CMCs [6]. Pryce and Smith [7] investigated the effect of interface partially debonding on the hysteresis loops of unidirectional CMCs by assuming purely frictional load transfer between fibers and the matrix. Ahn and Curtin [8] investigated the effect of matrix stochastic cracking on the hysteresis loops of unidirectional CMCs and compared with the Pryce–Smith model [7]. Solti et al. [9] investigated the effect of interface partially and completely debonding on the hysteresis loops of unidirectional CMCs using the maximum interface shear strength criterion to determine the interface slip lengths. Vagaggini et al. [10] investigated the effect of interface debonded energy on the hysteresis loops of unidirectional CMCs based on the Hutchinson–Jensen fiber pull-out model [11]. Cho et al. [12] investigated the evolution of

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interface shear stress under cyclic-fatigue loading from frictional heating measurements. Li [13] developed an approach to predict the damage evolution in CMCs under fatigue loading using a hysteresis loss energy-based parameter. Kuo and Chou [14] investigated the matrix cracking in cross-ply CMCs and classified the multiple cracking states into five modes, in which matrix cracking mode 3 and mode 5 involve the matrix cracking and interface debonding in the 0° plies. Lamon [15] distinguished the matrix multicracking of 2D woven CMCs into three main steps, and illustrated the schematic diagram showing the evolution of matrix multicracking. It was found that matrix cracking mode 3 and mode 5 also existed in 2D woven CMCs.

The objective of this paper is to compare the fatigue behavior of C/SiC and SiC/SiC composites under cyclic fatigue loading at elevated temperatures using hysteresis dissipated energy. The evolution of fatigue hysteresis dissipated energy and hysteresis dissipated energy-based damage parameter of C/SiC and SiC/SiC composites at elevated temperatures in air or steam condition have been analyzed. By comparing the experimental hysteresis dissipated energy with theoretical computational values, the interface shear stress corresponding to different cycle number, fatigue peak stress and test conditions have been estimated. The differences between C/SiC and SiC/SiC composites under fatigue loading at elevated temperatures have been analyzed.

2. Material and experimental procedures

The T-700™ carbon (Toray Institute Inc., Tokyo, Japan) fiber-reinforced silicon carbide matrix composites (C/SiC CMCs) were provided by Shanghai Institute of Ceramics, People's Republic of China [16]. The fibers have an average diameter of 7 μm and come on a spool as a tow of 12 k fibers. The cross-ply C/SiC composite was manufactured by hot-pressing method, which offered the ability to fabricate dense composite via a liquid phase sintering method at a low temperature. The volume fraction of fibers was about 40%. The dog bone-shaped specimens, with dimensions of 123 mm length, 3.8 mm thickness and 10 mm width in the gage section of cross-ply C/SiC composite, were cut from 150 mm × 150 mm panels by water cutting. The tension–tension fatigue experiments at 800 °C in air were conducted on a MTS Model 809 servo hydraulic load-frame (MTS Systems Corp., Minneapolis MN) equipped with edge-loaded grips. The fatigue tests were conducted under load control in accordance with the procedure in ASTM standard C 1360. The fatigue experiments were in a sinusoidal wave form and a loading frequency of 10 Hz, and stress ratio of 0.1.

3. Stress analysis

The stress distribution of the damaged composites upon first loading of the undamaged composites to fatigue peak stress is investigated in this section. In order to model the response of a cross-ply or 2D woven laminates, the composite is considered to be composed of three entities, i.e., the transverse tow, the fiber in the longitudinal tow, and the matrix in the longitudinal tow. The total thickness of the longitudinal and transverse tow are $2b$ and $2d$, respectively. The fibers are assumed to be prismatic and uniformly spaced throughout matrix of each tow. Upon first loading to fatigue peak stress σ_{max}, which is higher than the initial cracking stress of transverse and longitudinal ply or yarn, it is assumed that transverse cracks and matrix cracks would extend throughout the entire laminate cross-section. The multicracking modes in the cross-ply or 2D woven CMCs can be classified into five different modes, i.e., mode 1: transverse cracking in the transverse tow, with debonding at tow boundary; mode 2: transverse cracking and matrix cracking with perfect fiber/matrix bonding, and fracture of fibers occurs in the longitudinal tow; mode 3: transverse cracking and matrix cracking with fiber/matrix debonding and sliding in the longitudinal tow; mode 4: matrix cracking with perfect fiber/matrix bonding, and fracture of fibers occurs in the longitudinal tow; and mode 5: matrix cracking and fiber/matrix interface debonding and sliding in the longitudinal tow, as shown in Fig. 1. The fiber/matrix interface debonding and sliding only occurs in the mode 3 and mode 5. The stress analysis for mode 3 and mode 5 is given as follows.

3.1. Stress analysis of mode 3

The unit cell of mode 3, which contains transverse crack and matrix crack at the same cross section with fiber/matrix interface debonding in the longitudinal tow, is illustrated in Fig. 1(d). The length of the unit cell is $l_c/2$, which is the half matrix crack space. The interface debonded length is l_d. It is assumed that the stress in the transverse tow is not affected by the matrix cracks in the longitudinal tow. The axial stress distributions of fiber $\sigma_f(x)$, matrix $\sigma_m(x)$ and transverse tow $\sigma_t(x)$ are given by Eqs. (1)–(3), where σ referring to Fig. 1(a) denotes the stress applied on the composite.

$$\sigma_f(x) = \begin{cases} \frac{1}{V_f}(1+k)\sigma - \frac{2\tau_i}{r_f}x, & x \in (0, l_d) \\ \sigma_{fo} + \left[\frac{1}{V_f}(1+k)\sigma - \frac{2\tau_i}{r_f}l_d - \sigma_{fo}\right]\exp\left(-\rho\frac{x-l_d}{r_f}\right), & x \in (l_d, l_c/2) \end{cases} \quad (1)$$

$$\sigma_m(x) = \begin{cases} 2\tau_i\frac{V_f}{V_m}\frac{x}{r_f} - \frac{1}{V_m}k\sigma_t(x), & x \in (0, l_d) \\ \sigma_{mo} + \frac{1}{V_m}k(\sigma_{to} - \sigma_t(x)) - \left(\sigma_{mo} + \frac{1}{V_m}k\sigma_{to} - 2\tau_i\frac{V_f}{V_m}\frac{l_d}{r_f}\right)\exp\left(-\rho\frac{x-l_d}{r_f}\right), & x \in (l_d, l_c/2) \end{cases} \quad (2)$$

$$\sigma_t(x) = \sigma_{to}[1 - \exp(-\lambda x)], \quad x \in (0, l_c/2) \quad (3)$$

where r_f denotes the fiber radius; V_f and V_m denote the fiber and matrix volume fraction; τ_i denotes the fiber/matrix interface shear stress; $k = d/b$; ρ denotes the shear-lag parameter; σ_{fo}, σ_{mo} and σ_{to} denote the fiber, matrix and transverse tow axial stress in the interface bonded region, respectively.

$$\sigma_{fo} = \frac{E_f}{E_c}\sigma + E_f(\alpha_c - \alpha_f)\Delta T \quad (4)$$

$$\sigma_{mo} = \frac{E_m}{E_c}\sigma + E_m(\alpha_c - \alpha_m)\Delta T \quad (5)$$

$$\sigma_{to} = \frac{E_2}{E_c}\sigma + E_2(\alpha_c - \alpha_2)\Delta T \quad (6)$$

where E_f, E_m and E_c denote the fiber, matrix and composite elastic modulus, respectively; α_f, α_m, α_2 and α_c denote the fiber, matrix, transverse tow and composite thermal expansion coefficient; ΔT denotes the temperature difference between the fabricated temperature T_0 and test temperature T_1 ($\Delta T = T_1 - T_0$).